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Review of Potential Efficiency Improvements at Coal-Fired Power Plants

Introduction

The Clean Air Markets Division, U.S. Environmental Protection Agency requested that Perrin Quarles Associates, Inc., perform a review of readily available data on potential and actual efficiency improvements at coal-fired utilities. The objective was to identify heat rate reductions or efficiency improvements that have taken place due to either optimization efforts at existing utility boilers or due to the use of newer advanced technologies for coal combustion.

A unit's efficiency in this context refers to its thermal efficiency and is defined as a percentage determined by the electrical energy export divided by the fuel energy input. Fuel energy input can be defined either on a higher heating value (HHV) or lower heating value (LHV) basis. HHV is the full energy content of a fuel including the latent heat of vaporization of water, while LHV excludes the energy in the water vapor from the fuels hydrogen. The HHV will be about 5 to 10 percent higher than LHV. In the United States, fuel energy content is generally measured in terms of HHV, and HHV is used in Energy Information Agency statistics. Internationally, LHV is more often used. For this report, all efficiencies are reported on an HHV basis. Efficiency is also commonly represented by the heat rate, which is the reciprocal of the thermal efficiency and is described in the units of Btu/kWh.

This document discusses the range of heat rates and efficiencies associated with coal-fired power plants including the improved heat rates that have been achieved at some of the more recently constructed state-of-the-art coal-fired facilities. The following is a general discussion of this issue in the context of several different types of coal-fired plants. Note that the information in this report is based on a search of documents currently available on the Internet. More extensive research that may lead to additional data and supporting documentation could entail contacting EIA at DOE or individual facilities for additional information, particularly with respect to actual heat rates or efficiency percentages.

Conventional Pulverized Coal Plants

Current Heat Rates

Unit efficiency, or heat rate, is a function of unit design, size, capacity factor, the fuel fired, maintenance condition of the unit, and operating and ambient conditions (cooling water temperature). Existing pulverized coal boilers operating today in the U.S. use subcritical or supercritical steam cycles. A supercritical steam cycle normally operates above the water critical temperature (705 F) and critical pressure (3210 psia) where water can exist only in the gaseous phase. Subcritical systems historically have achieved thermal efficiencies of 33 to 34 percent (10,300 Btu/kWh to 10,000 Btu/kWh). Supercritical systems achieve thermal efficiencies 3 to 5 percent higher than subcritical systems.[1] Table 1 summarizes heat rate data for the 25 best performing utility coal-fired plants, and 50 best performing utility company coal-fired fleets in the U.S. The data were prepared for Electric Light and Power's annual top 100 utility operating report.[2]

Table 1: Best Coal Fired Heat Rates -- U.S. Utilities

	Lowest Reported Annual Average Heat Rate (Btu/kWh)	**Highest Reported Annual Average Heat Rate (Btu/kWh)**	**Average of the Reported Annual Average Heat Rates (Btu/kWh)**
25 Best Performing Coal-Fired Plants	8996	9486	9309
50 Best Performing Coal-Fired Fleets	9382	10,146	9854
Data on heat rates are taken from Electric Light and Power's annual top 100 utility operating report (EL&P, 1999), and were prepared by Navigant Consulting. Heat rates are from 1998 or 1997. The report noted that utility methods for determining the heat rate values are inconsistent.			

Heat Rate Improvements at Existing Plants

Many conventional pulverized coal-fired power plants have made improvements to their systems that have, in turn, led to improvements in the plant's efficiency or heat rate. The extent to which heat rates can be improved at existing plants is estimated to be at best 3 to 5 percent.[3] This is because heat rate is primarily dependent on unit design, fuel, and capacity factor, and the design of a plant can not be changed once built. The literature reviewed reported heat rate improvements consistent with the 3 to 5 percent improvement estimate.

Table 2 summarizes some of the potential actions that could be taken to improve plant efficiencies. Even though these data are based on the higher moisture "brown coal" or lignite typically used only in certain areas, such as Australia, Germany, Russia, and certain portions of the U.S., some of the actions may also be applied in the context of the lower moisture "black coal" or bituminous that is typically used in the U.S. These actions include those that would help restore the plant to its design conditions, change existing operational settings, or install retrofit improvements.

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[1]Kitto, J.B., Babcock & Wilcox, *Developments in Pulverized Coal-Fired Boiler Technology*, presented to the Missouri Valley Electric Association Engineering Conference, April 1996. http://www.babcock.com/pgg/tt/pdf/BR-1610.pdf

[2]Burr, M. T., Holding companies rule; top 10 sell 28% of U.S. electricity, Electric Light and Power, October 1999.

[3]Levy, E. and N. Sarunac, *Technical Review of EPA's Proposed Output Monitoring System*, Lehigh University Energy Research Center, September 2000.

Table 2: Measures that may Improve the Efficiency of Coal-Fired Power Plants[4]

Action*	Efficiency Improvement (%)
Restore Plant to Design Conditions	
Minimize boiler tramp air	0.42
Reinstate any feedheaters out of service	0.46 - 1.97
Refurbish feedheaters	0.84
Reduce steam leaks	1.1
Reduce turbine gland leakage	0.84
Changes to Operational Settings	
Low excess air operation	1.22
Improved combustion control	0.84
Retrofit Improvements	
Extra airheater surface in the boiler	2.1
Install new high efficiency turbine blades	0.98
Install variable speed drives**	1.97
Install on-line condenser cleaning system	0.84
Install new cooling tower film pack**	1.97
Install intermittent energisation to ESPs	0.32

* Note that the efficiency improvements expected as a result of implementation of these actions may not be additive and the feasibility and improvements associated with each action may vary based on plant configuration.
** The expected efficiency improvements associated with these actions may be overestimated.

Wisconsin Electric Power Company (WEPCO) has implemented a number of actions to improve the efficiency or heat rate at certain coal-fired plants, some of which are included in Table 2 above. The efficiency improvements as reported in the Climate Challenge Participation Accord between WEPCO and the Department of Energy (DOE) are summarized in Table 3. Efficiency improvements over a 5 year period ranged from 2.3 percent to 4.1 percent. In the Accord, WEPCO also committed to other efforts to improve heat rates including: various equipment control upgrades such as distributed control systems, precipitators and turbine controls; metering upgrades; boiler chemical cleaning; feedwater heater improvements; reduced condenser air in-leakage; and reduced

[4]Sinclair Knight Merz Pty. Ltd., *Integrating Consultancy - Efficiency Standards for Power Generation*, Australian Greenhouse Office, January 2000, p. 38. http://www.greenhouse.gov.au/markets/gen_eff/skmreport.pdf

thermal losses. WEPCO estimated a 0.5 percent annual company-wide heat rate improvement due to these additional efforts over a period from 1995 - 2000.

Table 3: Example Heat Rate Improvements at Wisconsin Electric Plants Due to Operational Changes (1990 - 1994)[5]

Plant	Original Heat Rate (Btu/kWh HHV)	Improved Heat Rate (Btu/kWh HHV)	Efficiency Increase (%)	Description of Efficiency Improvement Projects
Oak Creek	9,802	9,424	3.9	Variable pressure operation, distributed control system, retractable turbine packing, variable speed drives on the forced and induced draft fans, reduced air in-leakage, feedwater heater replacements, increased availability and capacity factor and precipitator energy management system
Pleasant Prairie	11,157	10,796	3.2	Variable pressure operation, unit and equipment performance monitoring, retractable turbine packing, reduced air in-leakage, increased availability and variable speed drive make-up water pumps
Presque Isle	11,565	11,089	4.1	Retractable turbine packing, increased availability and capacity factor, reduced air in-leakage, reduced excess boiler O2, boiler chemical cleaning, CO monitors on the boiler, improved turbine pressure and updated or additional instrumentation

[5]Wisconsin Electric Power Company Climate Challenge Participation Accord (agreement with DOE), Appendix A (Wisconsin Energy Emission Reduction/Sequestration Project Descriptions), Section 2 - Supply Side Energy Efficiency. http://www.eren.doe.gov/climatechallenge/cc_accordxWISCEL.htm

Table 3: Example Heat Rate Improvements at Wisconsin Electric Plants Due to Operational Changes (1990 - 1994) (cont.)

Plant	Original Heat Rate (Btu/kWh HHV)	Improved Heat Rate (Btu/kWh HHV)	Efficiency Increase (%)	Description of Efficiency Improvement Projects
Valley	13,938	13,623	2.3	Last row turbine blade replacement, retractable turbine packing, variable speed drives for the forced and induced draft fans, superheater surface change, reduced air in-leakage, reduced pulverizer primary air velocity and increased availability and capacity factor

PQA has previously reviewed literature for CAMD on NO_x reductions and efficiency improvements resulting from the installation of combustion optimization software, such as NeuSIGHT, ULTRAMAX, and GNOCIS. The software works with a boiler's digital control system to optimize and control boiler settings. Efficiency improvements from the combustion optimization ranged from 0.3 to 3 percent.[6]

New Pulverized Coal Plants

In addition to the potential for efficiency improvements at existing conventional pulverized coal-fired plants through operational changes and equipment upgrades, there is also the potential for dramatically reduced heat rates through the use of pulverized coal-fired power plants built with more advanced technologies.

A Low Emissions Boiler System (LEBS) based on the direct combustion of pulverized coal emphasizes improvements in technology and processes that are already widely accepted. These types of facilities include a high-efficiency pulverized coal boiler integrated with other more efficient combustion techniques and advancements in emission control technologies. The more advanced versions of these facilities may achieve up to 44 percent efficiency and are expected to be currently commercially available.[7]

In the context of these newer units, a 400 MW pulverized coal power plant design based on the utilization of pulverized coal feeding a conventional steam boiler and steam

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[6]Perrin Quarles Associates, Inc., *Review of Utility Coal-Fired Boiler Optimization Papers*, Appendix, August 2000.

[7]Lester, E., *Minimization of Global Climate Change Using Clean Coal Technology*, American Institute of Chemical Engineers, August 1998, p. 5. http://www.aiche.org/government/pdfdocs/cleancoal.pdf

turbine, as well as state-of-the-art technology and components currently available in the market, could achieve heat rates as low as 8,251 Btu/kWh, depending on the specific design of the facility. Design data for these types of facilities are summarized in Table 4 below.

Table 4: Heat Rate Data for Subcritical, Supercritical, and Ultra-Supercritical Coal-Fired Power Plants (Design Data Based on a 400 MW Facility)[8]

Type of Plant	Steam Pressure (psig)	Steam Temperature (F)	Expected Heat Rate (Btu/kWh)
Subcritical (conventional pulverized coal plant with emission control systems to meet current air quality standards)	2400 psig	1000F/1000F	9,077
Supercritical (single reheat configuration with emissions control systems to meet air quality standards expected in 2005)	3500 psig	1050F/1050F	8,568
Ultra-Supercritical (double reheat configuration with emissions control systems to meet air quality standards expected in 2010)	4500 psig	1100F/1100F/1100F	8,251

Another source includes data from coal-fired plants in North America, Europe, and Japan, and cites the best practice thermal efficiency rates at 37.7 percent and 41.7 percent for subcritical and supercritical plants, respectively, for facilities similar in size to those referenced above.[9]

An examination of this new generation of coal burning plants internationally have revealed that several are capable of achieving efficiencies above 40 percent through the use of low condenser pressures, high steam pressures and temperatures, double reheat cycles, up to ten stages of feed heating and other changes to station parameters and

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[8]U.S. Department of Energy, Office of Fossil Energy, *Market Based Advanced Coal Power Systems*, Section 3 -- Pulverized Coal-Fired Plants, May 1999, DOE/FE-0400, p. 3.1-5, 3.2-2, and 3.3-2.
http://www.fetc.doe.gov/coal_power/special_rpts/market_systems/market_sys.html

[9]Sinclair Knight Merz Pty. Ltd., *Integrating Consultancy -- Efficiency Standards for Power Generation*, Australian Greenhouse Office, January 2000, p. 6.

configuration of equipment. These plants and their corresponding efficiencies are summarized in Table 5 below.

Table 5 - International "Black Coal" Power Plants with High Design Thermal Efficiencies[10]

Plant	Online	Size (MW)	Steam Temperature (F)	Design Thermal Efficiency (%) HHV
Staudinger 5	1992	550	1004/1040	41.1*
Rostock	1994	550	1004/1040	42
Esbjerg	1992	400	1036/1040	43.2*
Nordjylland-svaerket	1998	400	1076/1076/1076 (double reheat cycle)	44.9
Lubeck	1998	440	1076/1112	43.6
Bexbach II	2002 (projected)	750	1067/1103	44.2

* Note that these estimated thermal efficiencies have been confirmed through testing and/or operating experience.

Combined Cycle Operations at Coal-Fired Power Plants

Coal-fired power plants have historically been limited to the simple cycle method. However, recent technological developments have led to the capability of powering "combined-cycle" generators. Under DOE Initiatives, two new technologies -- Pressurized Fluid Bed Combustion and Integrated Gasification Combined Cycle (IGCC) -- have allowed for combined cycle operations in the context of coal-fired facilities. These facilities have dramatically improved efficiencies or heat rates as compared to conventional pulverized coal-fired facilities.

Pressurized Fluid Bed Combustor

One study examined the efficiency benefits of using more advanced technologies such as the pressurized fluid bed combustor. Using a standard pulverized coal plant (294 MW with a heat rate of 9009 Btu/kWh) as a reference point, the efficiency benefits of using more advanced technologies were evaluated. A facility similar to the reference plant that utilizes a pressurized fluid bed combustor system may be able to achieve heat rates between 7,040 Btu/kWh and 8,679 Btu/kWh depending on the type of technology. A "bubbling bed" pressurized fluid bed combustor could lead to a heat rate of about 8,679 Btu/kWh, while a "first generation" or "second generation" pressurized fluid bed

[10]Sinclair Knight Merz Pty. Ltd., p. 59.

combustor could lead to heat rates of 8,506 Btu/kWh and 7,040 Btu/kWh, respectively.[11] Another DOE study also confirms heat rates in this range for a pressurized fluid bed combustor.[12]

Combustors the size of 70 to 80 MW have been in operation for a number of years. Recently, some larger combustors have been constructed. A 350 MW combustor is under construction in Japan and the expected efficiency is 41 percent. There is the potential to reach 43 percent in future plants. However, based on operational data from one existing plant, the overall net efficiency is approximately 38.2 percent.[13]

Integrated Gasification Combined Cycle

The DOE/Parsons study referenced above also examined the benefits of using an Integrated Gasification Combined Cycle (IGCC) system, which is capable of achieving heat rates between 7,374 Btu/kWh and 7,581 Btu/kWh, depending again, on the type of technology used.[14]

There have been some successful examples of plants that have recently demonstrated the IGCC technology. The Wabash River Coal Gasification Power Plant in West Terre Haute, IN and the Polk Power Plant in Polk County, Florida are two IGCC systems that have been successful at improving efficiencies. The Wabash River project repowered the oldest of six pulverized coal units using a "next-generating" coal gasifier, an advanced gas turbine and a heat-recovery steam generator. The 265 MW unit began operation in December 1995 and the design heat rate for the repowered unit is 9,034 Btu/kWh (approximately 38 percent efficiency).[15] The Polk Power Plant has a similar efficiency estimated at 39.7 percent and the heat rate is estimated at approximately 8,600 Btu/kWh.[16]

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[11]Bonk, D., and M. Freier, U.S. Department of Energy, and Buchanan, et. al., Parsons Power, *Assessment of Opportunities for Advanced Technology Repowering*, p. 3. , Proceedings of the Advanced Coal Based and Environmental Systems Conference, Pittsburgh, July 22 - 24, 1997. http://www.fetc.doe.gov/publications/proceedings/97/97ps/ps_pdf/PS1-7.PDF

[12]*Market Based Advanced Coal Power Systems*, Section 5 -- Circulating Pressurized Fluid Bed Combustor, U.S. Department of Energy, May 1999, p.5-5.

[13]Sinclair Knight Merz Pty. Ltd., pp. 59-60, 66-67.

[14]Bonk, D. and M. Freier, and Buchanan, et. al., p. 3-4.

[15]*DOE Fossil Energy Techline*, "Fourth Clean Coal Plant to Win Powerplant Award Sets Record Operation for Coal Gasifier in Early 1997." February 18, 1997. http://www.fe.doe.gov/techline/tl_wab96.html

[16]*Clean Coal Today*, "Tampa Electric's Greenfield IGCC Ready for Demonstration," Office of Fossil Energy, U.S. Department of Energy, DOE/FE-0215 P-24, No. 24, Winter 1996.

Recent data on actual operational results shows that these facilities have achieved efficiencies that are similar to the design values. The overall net thermal efficiency for the Wabash River IGCC facility has been 39.7 percent.[17] The overall net thermal efficiency for the Polk Power Station has been 36.5 percent with an overall heat rate of 9350 Btu/kWh. The efficiency for the Polk Station has been slightly lower than expected due to problems with the gasifier and low carbon conversion. These and other issues have been recently addressed and certain operational changes are expected to lead to a thermal efficiency of around 38 percent.[18]

One study notes that the efficiency of IGCC plants is expected to be around 42 percent and there is the potential to achieve 49 percent when higher efficiency gas turbines become available.[19] One DOE study estimates the thermal efficiency of an IGCC plant slightly lower at 40.1 percent with a heat rate of 8,522 Btu/kWh. This estimate assumes a 540 MW facility with a plant configuration based on the technology demonstrated at the Wabash IGCC facility but incorporates a new steam turbine. However, this study also describes IGCC facilities of similar size based on more advanced technologies (some of which of which are not yet commercially available) that could achieve an efficiency and heat rate of up to 49.7 percent and 6,870 Btu/kWh, respectively.[20]

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[17]"The Wabash River Coal Gasification Repowering Project - An Update," *Clean Coal Technology*, Topical Report #20, September 2000. http://www.lanl.gov/projects/cctc/topicalreports/documents/topical20.pdf

[18]"Tampa Electric Integrated Gasification Combined-Cycle Project - An Update," *Clean Coal Technology*, Topical Report #19, July 2000. http://www.lanl.gov/projects/cctc/topicalreports/documents/topical19.pdf

[19]Sinclair Knight Merz Pty. Ltd., pp. 59, 66.

[20]*Market Based Advanced Coal Power Systems*, Section 4 -- Integrated Gasification Combined Cycle, DOE, May 1999, p. 4.3-5.